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1000 MEGABITS PER SECOND INTERSATELLITE LASER COMMUNICATIONS SY--ETC(U)
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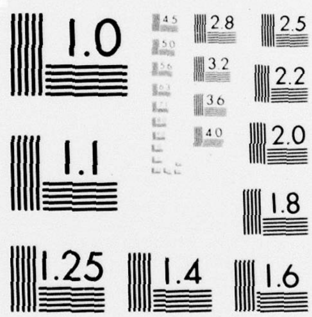

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1000 MEGABITS PER SECOND INTERSATELLITE LASER COMMUNICATIONS SYSTEM TECHNOLOGY

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ABSTRACT

The technology advances made in the development of an engineering feasibility prototype space qualifiable model of a Nd:YAG laser communication system for space test are discussed. The model includes the baseplate, opto-mechanical structure, 19cm (7.5 inch) diameter telescope and prototype space qualifiable components. The main technological achievements are in the areas of the laser and its operation, the modulator and the digital modulation format, and the integration of the various optical components into one opto-mechanical structure. These as well as other technology advances will be discussed, the system performance capabilities will be indicated, and a mock up will be available for viewing.

INTRODUCTION

The Air Force Program 405B for space laser communications began in 1971. The initial requirement was for a satellite laser system operating at 1000 megabits per second. Various laser systems were evaluated with the data rate requirement placed foremost. It was easily determined by simple analytical models that only two lasers had the necessary potential, the CO_2 laser and the Nd:YAG laser. Evaluation of the state of the art of the various components needed for a laser communications system indicated that only the Nd:YAG laser offered the most potential for 1000 megabit per second capability. The 405B Program, was, therefore, committed to the Nd:YAG concept.

It was initially established that the management philosophy of the 405B Program would be for the verification of the needed technology before commitment to a large systems venture. Technological developments were undertaken and the results evaluated with regards to their systems application. The system development was furthered by considering each component individually, and optimizing each for maximum performance. The 405B Program has progressed from purely technological and component development through preliminary subsystem designs, brassboard systems hardware and an engineering feasibility model of the system.

The engineering feasibility model has been the culmination of all the development work since 1971. The engineering feasibility model transmitter package was designed and fabricated to the flight qualification levels of the Defense Meteorological Satellite Program - Block 5 system. The engineering feasibility model package was tested to the flight hardware acceptance levels. The system and its components survived the thermal and vibration tests without significant degradations. The technology for a visible space laser communications system is the state of the art.

We are now entering this year into the development of a satellite package for launch in 1979. The space flight test will have the Air Force Nd:YAG laser package and may have a CO_2 laser package from NASA, and may also include a Navy experiment. The two packages will be operationally independent. The Nd:YAG system will operate at 1000 megabits per second and the CO_2 package will operate at 100-300 megabits per second[1]. The satellite will be launched into a highly elliptical orbit with apogee at synchronous altitude and a 12 hour period. The satellite apogee is to be at 100° west longitude and 60° north latitude once every 24 hours. The satellite will be near apogee for 5-6 hours, and the satellite will be simultaneously accessible from the Air Force ground station at Cloudcroft, New Mexico, and from the NASA ground station at Goddard Space Flight Center in Greenbelt, Maryland. The joint DOD/NASA space laser communications experiment will establish the feasibility of both Nd:YAG and CO_2 laser communications for space roles in the 1980s.[2]

The overall concept and discussion of the Nd:YAG laser communications system has been presented before and will not be repeated here in such detail [2-7]. The requirements for a space Nd:YAG laser system are essentially those of any satellite borne system for the conservation of weight, power, and volume but with the added problem of maintaining very fine optical characteristics and tolerances.

As an indication of the requirements for the satellite package, we have summarized the requirement parameters for the package for one communication link in Table 1. The present engineering feasibility model has been developed to achieve these capabilities. The technological state of the various components defines the system capabilities. By technological state, we mean that performance achieved with the particular component when it is being operated as if it were in a system. We have found that technological achievements demonstrated in the laboratory are not necessarily transferrable to near term application. The technological advances which we describe here are those which are system applicable, compatible, and have been system tested. We discuss the major technological advancements which have brought the 1000 megabit per second intersatellite laser communications system to its present state.

Wavelength λ	532nm	Dia. Rec. Ant.	47.7 cm
Beam Divergence	5.4μrad	Dia. Scan Flat	28cm
Dia. Tr. Ant.	20cm	Power	
Tr. Ant. Eff	0.75	Margin	6dB
Tr. Optics Trans	0.70	Optical	100mW
Dia. Scan Flat	28cm	Laser (Lamp)	260W
Rec. Ant. Eff	0.8	Modul/Driver	60W
Rec. Optics Trans	0.49	Electronics	54W
Rec. FOV	100μrad	A/T	72.4W
Filter Width	10Å	Pkg, Total	496.4W
Photocathode QE	0.2	Weight	
Excess Noise	2dB	Laser	12.7Kg
Bit Error Rate	1x10^{-6}	Modul/Elec	13.6Kg
Pointing Loss	0.94	Telescope	2.3Kg
Pointing Error	1μrad	A/T	23.8Kg
Modulation Depth	1.0	Structure	10.5Kg
		Pkg, Total	66.8Kg

Table 1. Package requirements for low earth orbiting satellite.

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LASER TECHNOLOGY

The evaluation of the capabilities of the Nd:YAG laser, and the status of technology for detectors and modulators led to the choice operation at the frequency doubled λ532 nanometers rather than at the fundamental λ1064 nanometers. The high data rate information is transmitted on λ532 nanometers laser light and λ1064 nanometer laser light is used as a beacon for the transmitter terminal from the receiver terminal. The

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λ532 nanometer light is the beacon for the receiver terminal.

The manner of optical pumping of the laser is different for applications with the low earth orbiting satellite, and synchronous or super-synchronous satellites. When the satellite can remain in sunlight for extended periods, then solar pumping will be used. The KRb lamp will be used for low earth orbit applications. A possible configuration of a satellite with solar pumping of the laser is illustrated in Figure 1. A flat reflector is used to direct the solar light down into the satellite and into a solar collector used to focus the light into the laser. By having the solar telescope within the satellite rather than mounted outside, we eliminate serious optical and mechanical difficulties associated with pointing and tracking of the solar energy and the resulting laser light.

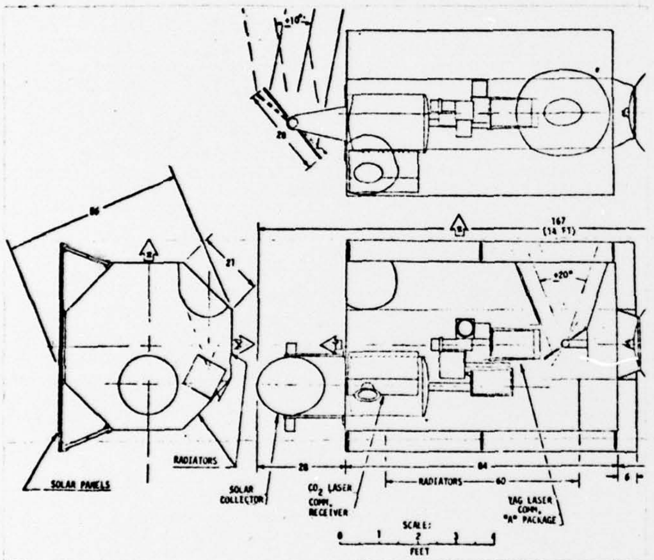

Fig. 1. Satellite Configuration.

The solar pumped laser is similar to the engineering feasibility model lamp pumped laser in optical and mechanical design. The difference being the manner of optical pumping. The solar pumped laser collector for space will have a diameter of 45.7 to 61 cm (15 to 24 inches) and is a Cassegrain structure. The solar pumped laser has the advantage of extended life expectancy and higher efficiency than the lamp pumped laser. The solar light will be filtered before incidence upon the laser rod to eliminate UV and IR wavelengths. The solar pumped laser may use a Nd:Cr:YAG rod rather than Nd:YAG since there is some evidence that the Cr increases the gain due to absorption in the λ400 to λ600 nanometer region. The thermal perturbations are somewhat greater with Nd:Cr:YAG and we are currently evaluating the solar pumped laser for optimum operating conditions. The solar pumped laser has generated over 400mW of λ532 nanometer laser light.

The KRb lamp for the lamp pump laser is an air operated, KRb filled, arc lamp, and development of the lamp for space use has not been completed. Our early problem areas included inadequate end seals, rapid frosting of the highly polished sapphire envelope, and voltage control problems. Significant advancements have been made in these problem areas during the last year. Frosting was greatly inhibited by adopting a larger bore size, the use of a getter external to the bore, and improving the lamp processing. Controlability was greatly improved by providing direct thermal contact between the reservoir heater assembly and the cold spot control point. Maximum lifetime was once limited to 40 hours and few on-off cycles. We are fabricating lamps now not for lifetime, but rather for cycle evaluation and reliability of the seals. One design, using a bare nickel end cap is, at this writing, achieving consistent 15-20 cycle, 200-300 hour lifetimes. The associated lamp lifetime would be significantly longer. A second design uses a chemical vapor deposition-CVD applied niobium end seal with a protective end bell structure. The niobium end seal design is being tested at the subassembly level and no actual lamps have been constructed. We believe both these designs have the capability of becoming long life structures usable in a lower earth orbit lamp pumped laser. Lamps have been thermally and vibrationally tested and survived.

The engineering feasibility model laser and the solar pumped laser both use an optically folded three-mirror laser configuration for optimum operation. The laser uses an intracavity lens to collimate the intracavity beam in the laser rod, and to focus the beam properly into the mode-locking, frequency doubling element. The intracavity lens is placed near the confocal position for thermal and mechanical insensitivity. The folded configuration is used to achieve two pass interaction in the frequency doubling crystal, sum the frequency doubled laser light, and direct it out of the laser in one direction. The laser rod is conductively cooled since liquid cooling was unacceptable for satellite operation. In addition, the laser pump cavity has its elliptical surface coated with a dielectric coating which reflects only the pump band radiation between λ700 and λ1000 nanometers, and absorbs most of the other wavelengths.

The operation at λ532 nanometers is achieved by intracavity frequency doubling with a crystal of Barium Sodium Niobate, $Ba_2Na(NbO_3)_5$. The crystal is thermally maintained at the phase match temperature where the indexes of refraction at λ1064 and λ532 nanometers are equal, and optimum generation of λ532 nanometer light may be achieved. $Ba_2Na(NbO_3)_5$ crystals have been commercially available since about 1969. However, we use crystals with extremely low absorption losses specifically grown for this program and evaluated in our laboratories[8].

Crystal absorption of λ1064 and λ532 nanometer light is deleterious to the laser operation since the crystal is placed within the optical cavity. We measured absorption coefficients of order, α(1.06) 0.01 cm^{-1} in the period 1972-1973. We now have crystals with absorption coefficients of order, α(1.06 0.001 cm^{-1} [9]. The visible wavelength absorption coefficients may be 10 to 50 times higher, but they are not as critical as the λ1064 nanometer absorption since the gain of the laser is only about 3%. The optical quality of the crystal has also been improved significantly. As a result, there is less optical distortion in the beam. The much improved quality of the recent crystals has been an important advancement in the past year which has enabled increased laser performance to be achieved.

We use $Ba_2Na(NbO_3)_5$ crystal not only as a frequency doubler but also as a mode locking element for the laser. The use of the $Ba_2Na(NbO_3)_5$ crystal in the dual role of acousto-optical mode-locker and frequency doubling device has resulted in considerable improved operation[10]. The earlier brassboard laser used a combination of a quartz acousto-optical mode locker and a

$Ba_2Na(NbO_3)_5$ electro-optical mode locker. It required complex electronic circuitry to drive both mode lockers simultaneously and to phase the drive signals properly to produce a relatively stable mode locked train of laser pulses. The engineering feasibility model laser incorporates only the one $Ba_2Na(NbO_3)_5$ acousto-optical mode-locker, has been extremely simple to operate, and is much more stable than previous lasers. A depth of modulation of 2% is presently achieved with only 1 watt to the acousto-optical mode-locker. A time dependent analysis of the laser illustrated that the oscillation damping factor is increased by frequency doubling [11]. Consequently, the λ 532 nanometer operation with the Nd:YAG laser is more stable than the λ 1064 nanometer operation. The engineering feasibility has an amplitude instability of about 0.2%.

In order to improve mechanical stability and, more importantly, increase power, the engineering feasibility model laser was a new optical and mechanical design. The lamp pumped frequency doubled Nd:YAG laser for space must operate with a potassium-rubidium (KRb) lamp due to the low input power requirements. Consequently, the lamp to rod interaction was carefully evaluated. In addition to the distortion of the laser rod due to the thermal load from the lamp[11], we found by fluorescence tests that the KRb lamp arc image can pump the laser rod in a non-uniform manner, and the 1064 nanometer power can thermally distort the intracavity frequency doubling crystal.

Experiments were performed to evaluate the influence of thermal lensing, thermally induced birefringence, and the arc image distribution in the rod. It was found that the rod was thermally distorted with the KRb lamp and the thermally induced lens in the rod had a focal length of 140 cm, as compared to 250-300 cm with the water cooled Krypton (Kr) lamp operation of the same laser[12, 13]. The evaluation of thermal birefringence and fluorescence distribution of three identical laser rods operated in the laser pump cavity and pumped with a KRb lamp led to a change in the rod dimensions from 3x54.5 mm with earlier lasers to 4x66 mm. An example of a KRb lamp pumped 4mm rod birefringence distribution is shown in Figure 2. A 1.5 mm beam in the rod can be supported which improves the laser performance.

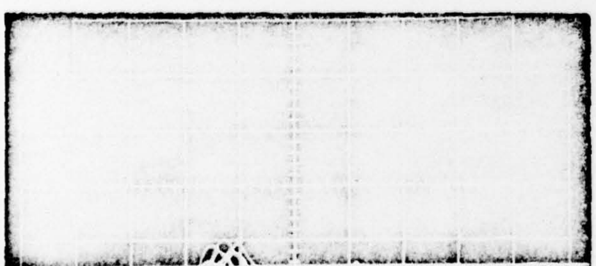

Fig. 2. Birefrigence distribution in a 4 mm KRb lamp pumped Nd:YAG laser rod indicating 1.5mm clear center.

We have achieved an optimum laser optical resonator design by using an in-house analytical computer model which included KRb lamp data, the rod fluorescence and birefringence data, the $Ba_2Na(NbO_3)_5$ data, as well as the induced thermo-optical effects. The absorption of 1.06 micrometer light in the frequency doubling crystal causes a lens effect and a diffraction loss which were included in the optical design[14]. The output power of the engineering feasibility model laser has been more than twice that measured with the brassboard laser. The Kr lamp pumped engineering feasibility model laser has generated over 250 mWatt of mode locked λ 532 nanometer power with 10% to 10% pulse widths of less than 300 ps[15]. Performance with the KRb lamp will be reported during the presentation.

Two theoretical treatments of the mode-locked frequency doubled Nd:YAG laser were also generated[16, 17]. Both describe the observed laser performance with good agreement relative to power and pulsewidth. Experiments are underway to determine which is more accurate with respect to pulsewidth predictions.

The laser is constructed from a single piece of invar for maximum thermal and structural stability. The optical elements are firmly mounted and the end mirrors have slight adjustments by means of locking flexure mounts. The laser rod and pump cavity are differentially conductively cooled by separate heat pipes so that the rod may be kept at 0°C or less and the cavity at 20°C. The laser operated within about 90% of its initial power after the vibration tests in spite of Qs greater than 100. This is the first time that a solid state laser has been designed and fabricated to withstand a launch environment and operate hands-off. The laser will, of course, be modified to reduce the Qs for the space qualified unit. A photograph of the laser mounted for vibration testing is shown in Figure 3.

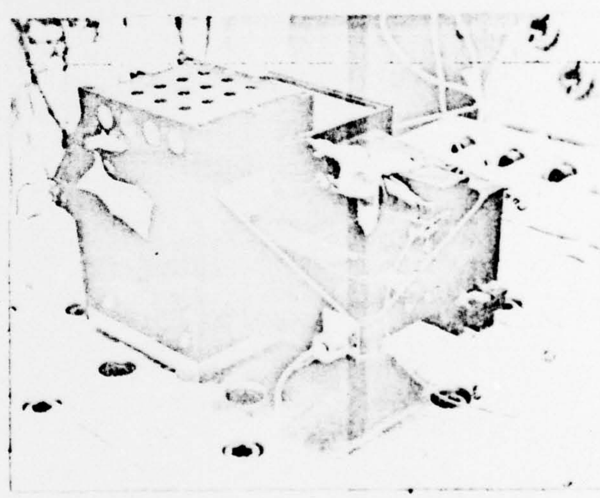

Fig. 3. Photograph of the engineering feasibility model laser mounted for vibrational testing.

MODULATOR TECHNOLOGY

The engineering feasibility model system uses a modulation data format different from that used in the brassboard system. A pulse quaternary modulation (PQM) is used rather than pulse gated binary modulation (PGBM) because of increased efficiency with PQM. We illustrate this increased efficiency in Figure 4 where the system operation at 1000 Mbps PQM and PGBM are compared. The system was operated asynchronously with zero background; asynchronous means that the laser rate and data rate are not synchronized to one another.

The modulator depth of modulation was 20/1 and the data codes used are indicated. The comparison is with the variables, bit error rate on the vertical axis and photoelectrons received per bit on the horizontal axis.

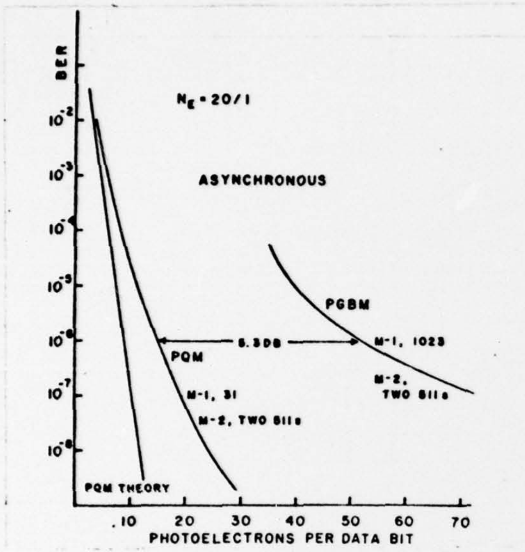

Fig. 4. Comparison of PQM and PGBM operation of the laser system.

The PQM format modulator uses one 500 Mbps and one 1000 Mbps modulator placed in series with a 1 nanosecond optical time delay unit between the two modulators. The PQM operation may be classified as a sequential series action. The polarization of an incident light pulse is rotated by 90° by the first modulator for a binary one or not rotated for a binary zero. Rotated and unrotated pulses then enter the optical undisturbed while the rotated pulse is time delayed by 1 nanosecond and then is optically recombined into the main optical path.

The combined pulse stream is then caused to enter the second modulator. The second modulator causes polarization rotation or non-rotation similar to the first modulator. The second modulator is coded electronically relative to the first modulator to account for the unequal time interval between pulses. The incident 500 megapulses per second light is thus coded in time and polarization to a 1000 Mbps data rate. A photograph of the engineering feasibility model PQM modulator is shown in Figure 5.

The electro-optical modulators are fabricated using two small tapered crystals of lithium tantalate, $LiTaO_3$. The use of $LiTaO_3$ rather than some other crystal material is also a technological advancement. $LiTaO_3$ has been historically difficult to obtain in the contaminant (particularly iron) free state. $LiTaO_3$ which has an iron content of only 2-10 ppm was developed for use inthese fast modulators[18]. This is over 100 times lower than is normally available. Optical damage was once a problem. The new material has been tested with optical densities of order 1×10^7 watts cm^{-2} for extended periods without deleterious effects.

Each modulator uses two $LiTaO_3$ crystals placed end to end. The crystals are 10 mm in length and are tapered along the length. The end dimensions are 0.25 x 0.25 mm and 0.15 x 0.25 mm. The crystals have their A-faces perpendicular to the incident laser light. The E and O axes of the two crystals are rotated 90° relative to the polarization of the incident laser light. The crossed axes configuration tends to self-compensate the natural birefringence of $LiTaO_3$ and reduces temperature sensitivity. The incident laser light is optically focused between two crystals with a beam waist of order 150×10^{-4} cm. A Rayleigh length of 10 mm is used to minimize the truncation loss of the system.

Fig. 5. Photograph of engineering feasibility model PQM modulator.

The modulator uses a solid state driver which provides a nominal 20 volt pulse with a rise and fall time of order 200 picoseconds. Each modulator requires about 30 watts, including driver and heater. The crystal temperature must be kept at 150°C to allow self annealing and eliminate possible optical damage. The voltage pulse must be applied to the crystals simultaneously with the passage of the optical pulse which has a 10% to 10% point pulse width of about 300 picoseconds. A precision retimer is provided in the premodulator electronics to synchronize the modulator drive to the master clock derived from the optically detected laser pulse rate at the laser.. The modulator optical transmission is currently about 0.50 with an expected improvement to about 0.75.

The main problem as of this writing is the optical coatings used on the crystals and other optical elements. We were using an antireflective optical coating of ThF_4 on the $LiTaO_3$. These coatings have shown a degradation with time which we speculate is due to oxygen migration from the $LiTaO_3$ to the surface which causes an index of refraction change at the ThF_4 interface. Consequently, the antireflection coating reflectivity increases to unacceptable values. We have adopted antireflective SiO_2 coatings which do not have the problems of ThF_4 coatings. Initial tests indicate a very low antireflection coating parameter for the SiO_2 surfaces and vastly improved stability with time.

OPTO-MECHANICAL STRUCTURE/TELESCOPE TECHNOLOGY

The opto-mechanical structure is the structural unit which firmly holds the components and optical elements of the transmitter package in critical optical and mechanical alignment. The engineering feasibility model opto-mechanical structure is essentially a cast aluminum shell which was accurately machined to the required tolerances. A photograph of the opto-mechanical structure is shown in Figure 6. The opto-mechanical structure without components and elements weighs 5.7 Kg (12.5 lb).The completed unit including

telescope, optical bender bimorphs, baseplate, and optical elements weigh approximately 10.9 Kg (24.0 lb). The weight of the three acquisition and tracking detectors is about 7.95 Kg (17.5 lb). The opto-mechanical structure is fabricated from type 8-A356-T77 heat treated aluminum for an optimum strain-elongation relation.

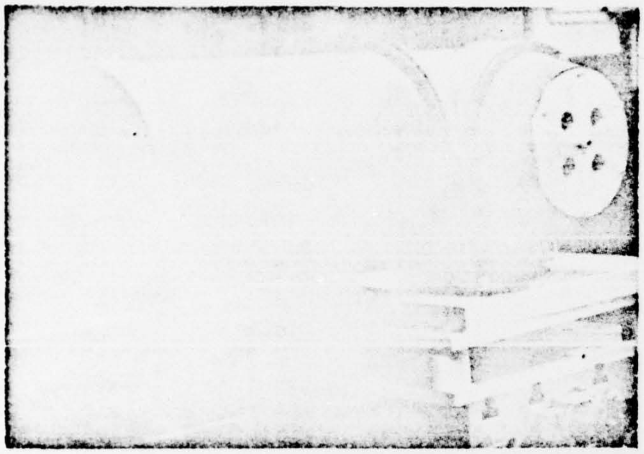

Fig. 6. Photograph of the opto-mechanical structure and telescope

The arrangement of the elements in the opto-mechanical structure is schematically shown in Figure 7. The λ532 nanometer laser light is directed out of the package by the two bender bimorph mirrors and then out the telescope. The orientation of the two bender bimorph mirrors is controlled by electronic signals derived from the coarse acquisition, fine acquisition, and fine tracking detectors. These detectors are quadrant detectors formed by a reflective pyramid and four individual λ 1064 nanometer sensitive detectors.

These detectors determine the direction from which the λ 1064 nanometer laser light is received from the beacon laser in the distant high data rate receiver. The pointing of each transmitter and receiver terminal laser beam is accomplished by tracking the laser light from the opposite terminal and using the tracking and point ahead bender bimorph mirrors. The λ 1064 nanometer laser light received at the transmitter terminal is collected by the same telescope and much of the same optics that are used to transmit the high data rate λ 532 nanometer laser light.

Acquisition between transmitter and receiver terminals is accomplished by sequentially detecting the beacon light in a narrower field of view. The incoming λ 1064 nanometer light is initially reflected by the bifurcating mirror onto the coarse acquisition detector. This detector drives the flat scanning mirror so that the λ 1064 nanometer light falls through the hole in the bifurcating mirror and on through the reflective optical train to the fine acquisition and fine tracking detectors. The tracking detector controls the orientation of the tracking bender bimorph mirror which centers the λ 1064 nanometer light on the fine acquisition detector. The beam is then directed to the fine tracking detector by the removal of the solenoid activated fine acquisition mirror. The distant high data rate receiver and the transmitter are thereby aligned, and controlled with provisions for point ahead angles by the bender bimorph mirrors in the λ 1064 nanometer optical train.

The optical efficiency of the system is also directly dependent upon the quality of the transmitter antenna - the optical telescope. The optical telescope developed for the engineering feasibility model is a 19.05 cm (7.5 inch) diameter Cassegrain which will provide a 5.4 urad full angle beam divergence. A telescope of this type for space use has not been fabricated before now. We have used beryllium as the primary material for the telescope and the telescope mirror substrait. The substrait is coated with Kanogen surface which is polished to the desired optical quality. The Kanogen surface is then coated with a silver reflective surface. The radius of curvature of the primary and secondary mirrors are 66.1277 cm and 139.3677 cm respectively, and the effective focal length of the telescope is 215.9 cm. The diameter of the primary and secondary mirrors are 19.05 cm and 3.81 cm, respectively. The optical quality of the telescope was designed to be better than $\lambda/8$. The measured optical quality of the finished telescope was $\lambda/13$ before and after vibrational testing.

The clear aperture telescope transmission is better than 95.5%. The total overall transmission at λ 1064 nanometer is 76% including the 4% obscuration loss. The λ 1064 nanometer transmission is about 64%. The telescope weight is 2.9kg (6.3 lb).

Various optical elements of the opto-mechanical structure have been evaluated with regards to their reflective performance. Based upon these early results, it is expected that the 1064 nanometer light reaching the fine acquisition detector will be 64% of that incident upon the telescope. A value of 50% was initially expected. The technology of reflective coatings has been improved substantially over the past two years, thereby improving the optical efficiency of the system.

A manufacturing problem became apparent during the fabrication of the telescope. The image quality

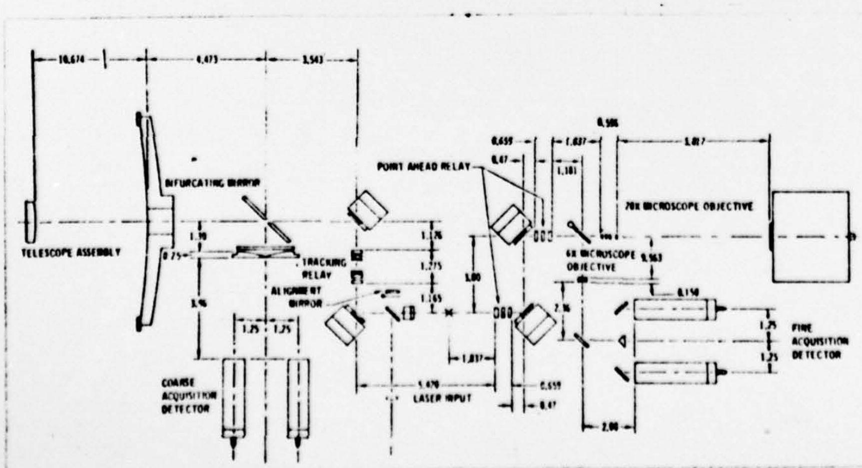

Fig. 7. Schematic of the optical arrangement of the transmitter package, engineering feasibility model.

required for the telescope was difficult to achieve and was caused by degradation of the inner 0.3 cm (1/8 inch) zone on the primary mirror. During polishing of the surface, the quality could be controlled to only $\lambda/4$ in the inner zone due to roll-over of the polishing tool. The outer 0.3 cm suffers the same problem. We now know that the fabrication of a telescope must be done with slightly enlarged blanks.

A major complication for space to space laser communications is the acquisition and tracking of the two widely separated space packages. Acquisition and tracking between a laser transmitter and receiver was evaluated with laboratory hardware[2]. The equipment was operated with the space distance simulated by the appropriate attenuation of the optical signal. Additionally, the relative motions between two space terminals were imposed on the laser beam through a gimballed mirror and a set of motion bender bimorph mirrors mounted between the transmitter and receiver terminals. The motion inputs included a simulated orbital motion with an angular velocity of 1200 μrad sec^{-1}, a limit cycle with an angular velocity of 2000 μrad sec^{-1}, an angular acceleration of 10 mrad sec^{-2}, and sinusoidal vibrations with frequencies from 10 to 50 Hz and amplitudes from 2 to 20 μrad peak to peak.

The pointing error measured with 2.4×10^{-10} watt of average power received from the λ 1064 nanometer beacon laser was less than 1.2 μradians peak to peak. This corresponds to beacon laser power of 100 mWatt for the low earth orbit to synchronous satellite link with a 6dB power margin. The overall result illustrated that a pointing error of 1 μrad peak to peak is within the capability of the existing technology.

CONCLUSIONS

The technology base for visible laser communications has been significantly advanced in the past few years. The component developments and the brassboard systems have proven the basic technology. The engineering feasibility model has proven the capability of fabricating visible laser space hardware. We are now at the threshold of developing the laser communication system package for space use. The space program planned is for the development and space flight test of a laser communication system for real time global relay of high data rate data. The space test will set the stage for laser efforts in the 1980s. The future of laser communication systems in space depends directly upon the results of this 405B Program.

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